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Future role of Hydrogen in the Netherlands

A meta-analysis based on a review of recent scenario studies

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Part of this report has been integrated in the general report of the HyChain 1 project.

Summary

This report explores the future role of hydrogen as energy carrier and feedstock in a low-carbon energy system, focusing on the Netherlands. In particular, it provides a review of the projected range in hydrogen use across various sectoral applications based on studies reported in the recent literature (2014-2019). In addition to studies focusing on the Netherlands only, for comparative reasons we have also reviewed other studies covering other EU countries, the EU as a whole or even the global energy system. This meta-analysis provides insight in the similarities and differences in assumptions and outcomes of the studies reviewed with regard to the future role of hydrogen in a low-carbon energy system.

In addition, we also indicate which factors appear to have the highest impact on the future role of hydrogen – in terms of hydrogen demand, supply, infrastructure and wider system functions – in the model scenarios and visions included in the reviewed studies. These factors are important to address in models to make better-informed projections and assessments of the future role of hydrogen in a low-carbon energy system.

The report shows that the reviewed studies present a wide range of outcomes with regard to the future role of hydrogen in the Netherlands, notably in terms of hydrogen demand across various sectoral applications. This large variety of outcomes is mainly due to differences in key determining factors and underlying assumptions of these studies. Often these factors and assumptions – including the implications for the resulting outcomes – are not addressed in an explicit and adequate way. In addition to identifying the required modelling features to analyze the future role of hydrogen in an integrated, low-carbon energy system, the report also discusses briefly the most relevant modelling parameters affecting this role. These parameters include in particular: (i) the CO_2 reduction target, (ii) the availability of carbon dioxide capture and storage (CCS), (iii) the availability of biomass, (iv) the supply of variable renewable energy (VRE), such as solar and wind energy power generation, and (v) the costs of hydrogen as well as competing energy demand and supply technologies.

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1 Introduction

To limit global warming, anthropogenic greenhouse gas (GHG) emissions have to be reduced to almost zero or even negative as soon as possible (IPCC, 2018). The combustion of fossil fuels results in the release of CO_2, which is the major contributor to overall GHG emissions and to climate change. To avoid the use of fossil fuels, a switch to renewable energy sources is of prime importance. These renewable energy sources have to be linked via climate neutral energy carriers to the final energy needs of for instance the built environment, industry and transport.

Renewable electricity is a good example of such an energy carrier. In combination with electrification of the end-use sectors, electricity can supply a significant share of renewable energy to society. Solar and wind energy are expected to be the main energy sources to deliver the renewable electricity. However, the intermittency of these sources poses challenges and introduces a significant demand for flexibility, including buffering and storage of renewable energy. Furthermore, it is highly unlikely that electricity will be the sole energy carrier of our future society. Currently, in the Netherlands, only around 20% of our final energy consumption is supplied by electricity. Electricity use is increasing but reaches in most scenarios a share of 40 to 60% of total energy demand at most (Eurelectric, 2018; IRENA, 2018). This suggests that 40-60% of future energy demand has to be provided by other climate-neutral energy carriers, for instance by renewable gaseous and liquid fuels.

Currently, biomass represents the main source for supply of renewable fuels and feedstocks, but the availability and sustainability of biomass remains a point of serious concern. Production of hydrogen by water splitting through electrolysis, driven by renewable electricity, may provide an addition or alternative to bio-based energy carriers. The ability to convert renewable electricity into hydrogen or other green fuels may also provide the flexibility required to optimally deploy solar and wind into a sustainable and reliable energy system. How will the mix of energy carriers change in the future and what are the alternative energy carriers and primary resources to achieve such a system? Can hydrogen be such an alternative and to what extent?

This report explores the future role of hydrogen as energy carrier and feedstock in a low-carbon energy system, focusing on the Netherlands. In particular, we provide a review of the projected range in hydrogen use across various sectoral applications based on studies reported in the recent literature (2014-2019). In addition to studies focusing on the Netherlands only, for comparative reasons we have also reviewed other studies covering other EU countries, the EU as a whole or even the global energy system. This meta-analysis provides insight in the similarities and differences in assumptions and outcomes of the studies reviewed with regard to the future role of hydrogen in a low-carbon energy system.

In addition, we also indicate which key factors appear to have the highest impact on the future role of hydrogen – in terms of hydrogen demand, supply, infrastructure and wider system functions – in the model scenarios and visions included in the reviewed studies. These factors are important to address in models to make better-informed projections and assessments of the future role of hydrogen in a low-carbon energy system. Therefore, in addition to reviewing the projected future role of hydrogen in the Netherlands, the current report also aims to identify the key factors and uncertainties affecting this role in order to improve the (integrated) energy system modelling and analysis of the future role of hydrogen.

2 Hydrogen today

Demand

Currently, a large share of total hydrogen demand in the Netherlands is used as feedstock for the production of ammonia and methanol, and in refineries for desulfurization, hydrogenation, and cracking of oil. Most other applications are also found in the industrial sector, for instance in the chemical industry, glass manufacturing, metallurgy, welding, and for cryogenic research (FCH2JU, 2019).

Supply

In Europe, the Netherlands is currently next to Germany the largest producer of hydrogen with an estimated annual volume of more than 10 billion cubic meters or 110 PJ/yr (DNV GL, 2017). Hydrogen is mainly produced by reforming of natural gas, and as byproduct of steam cracking of naphtha (olefin synthesis) and electrocatalytic brine conversion (chlorine production). Export of hydrogen (primarily to Belgium and France) accounts for approximately 9 PJ/yr, while import is below 1 PJ/yr (based on CBS data for 2015, accessed in April 2019). This indicates that domestic demand is currently around 100 PJ/yr and thus consumes most of the domestic hydrogen production.

Infrastructure

Production on site is the most common situation in the case of bulk industrial demand of hydrogen. With multiple users in an industrial cluster transport of hydrogen also occurs via dedicated pipelines. The total estimated network of large hydrogen pipelines globally accounts for more than 4500 km, of which almost 1600 km in Europe (H2tools, 2016). Hydrogen networks in the Netherlands exist from Air Products in the port of Rotterdam to local, clustered industries (140 km pipelines) and from Air Liquide from the Port of Rotterdam stretching via Belgium to the North of France, and a separate network in the Ruhr area in Germany (together around 1000 km of pipelines) (Figure 1, DNV GL, 2017). Recently, the industrial sites of Dow and Yara are connected with a 12 km hydrogen pipeline, which is operated by Gasunie (Gasunie, 2018b) and was used previously for natural gas transport.

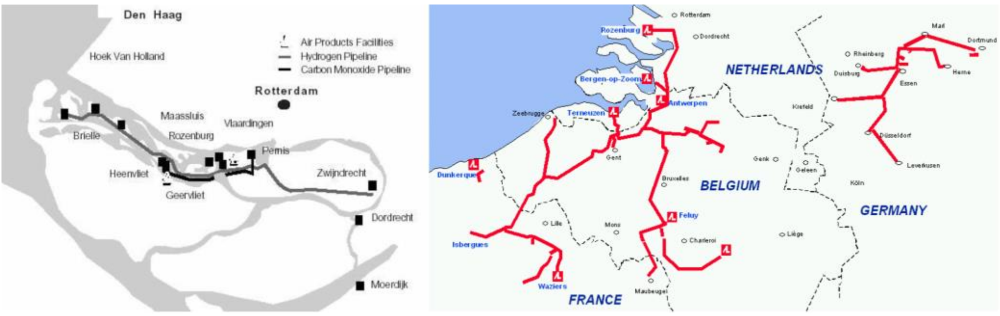

Figure 1: Existing hydrogen networks (left: Air Products; right: Air Liquide); source: DNV GL (2017)

Hydrogen is also transported by trucks to small-scale industrial customers and increasingly to refueling stations. Transport occurs either in gaseous form in high pressure cylinders or tubes, or in liquid form in cryogenic tanks (<−253°C). In principle, hydrogen can also be transported by trains, barges and ships.

3 Applications of hydrogen

Hydrogen is a versatile energy carrier and can be applied in various ways. We distinguish between five major categories for application of hydrogen as listed below. How we differentiate between hydrogen use for energy and non-energy purposes is defined in Annex B. More detailed information about different applications of hydrogen is provided in two recent studies, which also describe the systemic role of hydrogen and other power-to-X energy carriers (FCH2JU, 2019; Frontier Economics, 2018).

Low temperature heat (buildings)
Hydrogen can be used in gas networks (either directly as pure hydrogen gas or mixed with natural gas or bio-methane) to supply energy for space heating and in principle also for cooking in buildings.

Fuel for electricity generation (power)
To cope with the intermittency of renewable power generation, a certain share of power generation should be dispatchable to provide the required flexibility. During periods with less sun and wind, gas turbines or stationary fuel cell systems, both running on hydrogen, can respond quickly to provide electricity and stabilize the grid.

Fuel for transportation (transport)
In the transport sector battery electric vehicles (BEVs) are expected to take over a high share of road transport. Heavy duty transport, shipping and aviation are however more difficult to electrify, and other renewable fuels seem required. Hydrogen-driven fuel cell electric vehicles (FCEVs) may provide a solution for some of these applications such as buses, trucks and specialty vehicles. In addition, hydrogen can also be used for the conversion of biomass or CO_2 into biofuels and renewable synthetic fuels for transport applications such as planes and ships.

High temperature heat (industry)
Some industrial processes require high temperature heat. Currently this heat is mainly provided by the combustion of natural gas, which is delivered via the gas network. Similar as for low temperature heat, biomethane or hydrogen can be blended into the natural gas network for decarbonization. Alternatively, an increasing share of the network can be turned over to pure hydrogen.

Non-energy use of hydrogen (industry)
Industry consumes fossil resources also to produce various products. Most of these products eventually are incinerated, decomposed, or combusted with release of CO_2. Hydrogen is a versatile energy carrier and can be used as feedstock for the production of fertilizers, iron and steel, chemicals, and plastics. Industrial production of synthetic transportation fuels, as mentioned above (transport), will also increase hydrogen demand of industry, although in some studies this share of hydrogen use is ascribed to the transport sector.

These five categories of hydrogen application are ascribed to four different sectors as depicted above (between parentheses). Detailed knowledge about each of these sectors is required to obtain well-informed estimates of the potential role of hydrogen in each sector. Also, the cross-sectoral relationships and available alternatives are important to address.

Overall these insights will lead to a more adequate assessment of the future role of hydrogen in the energy system as a whole, including system aspects such as the reliability or balancing of the energy system. For instance, during periods of excess power production from sun and wind, electricity can be converted into hydrogen by ramping up electrolyser capacity as a demand response option to balance the electricity grid. Hydrogen can also play a role as seasonal storage option for the energy system as a whole – including electricity, gas and heat – thereby enhancing the reliability and balancing of the energy system based largely on renewable (intermittent) energy sources.

4 Approach: reviewing and comparing recent energy studies

To enhance our insight into the potential future role of hydrogen in the Netherlands we perform a meta-analysis of 18 recent studies (see: Appendix A). The scope of these studies varies significantly. In this section, we describe a few of these differences in dimensions, such as time horizon, type of scenario, geographic scope, type of scenario model (if applied in the studies), variety in sectors and applications, and clarify the methodology we follow to allow an adequate comparison.

Time horizon and emission reduction target
The type of vision or model scenario is often determined by a set of ultimate goals to be achieved. In most energy scenario studies, the most dominating policy objective refers usually to the reduction of GHG emissions, e.g. by 95% in 2050 (compared to 1990). Some studies aim for lower emission reductions: for instance, 50% if the time horizon does not go beyond 2030; or 80% in 2050 for less stringent scenarios. In this meta-analysis, we have mainly compared the reported findings for 2050 in the studies reviewed. If a study contains multiple scenarios for 2050 we have at least selected the one with the highest hydrogen use and/or with the highest emissions reduction target.

Region and country
It is highly unlikely that hydrogen becomes a substantial energy carrier only in the Netherlands. Therefore, for comparative reasons, we also included the projections for hydrogen use of some recent studies covering other regions and countries, such as case studies for other EU countries than the Netherlands or regional studies covering the EU or the global energy system as a whole. To compare these projections for a specific year (i.e., 2050) with the studies for the Netherlands, the numbers are corrected by the relative size of the Netherlands in terms of gross domestic product (GDP) as projected for that specific year (OECD, 2019; Shell, 2018). For instance, if the GDP of a country or region in 2050 is about ten times bigger than of the Netherlands, the numbers on projected hydrogen use of that country or region in 2050 have been divided by a factor ten.

Model or vision
Hydrogen demand and supply projections are either scenario outcomes by means of a (detailed) model or rough estimates based on a vision or roadmap. The modelled approaches can for instance provide a cost-optimized system, subject to a set of boundary conditions, or a simulated system based on an estimated supply-demand goal. The level of detail and the results vary among the models as they strongly depend on the assumptions made regarding their input parameters (e.g., economic growth, available technology options, their costs). Visions and roadmaps are typically underpinned storylines on how a system may evolve, though often lack economic analysis and comparison with alternative options and thus possess a higher order of uncertainty. We show results ranging from integrated assessment models to visions next to each other and discuss the differences between models and visions in Section 5.1.2.

Sectors and applications

Hydrogen demand in a specific sector is often dominated by one or two applications of hydrogen use as listed in Chapter 3. Some studies categorize hydrogen use per sector, while others classify per application. We have considered the listed applications in Chapter 3 as interchangeable with hydrogen use in a sector and often only refer to the latter. We shortly comment on our approach in the next paragraph.

In the built environment mainly low temperature heat is required, while high temperature heat is needed in industry. Industry is also the major demand sector for non-energy use of hydrogen. Hydrogen as fuel for mobility is covered by the transport sector and as fuel for electricity generation is subscribed to the power sector. We should note that this approach is to some extent causing deviations, e.g. heat use in industry is considered as high temperature heat only. Within the uncertainty range of the projections, these deviations in the projected hydrogen demand by certain applications or sectors are relatively small.

Not all studies include all sectors. The analysis by Dechema only covers industry (Dechema, 2017). In some studies, specific applications of hydrogen use are excluded. In the Sky scenario (Shell, 2018), for example, only energetic use of hydrogen is included, and the authors deliberately exclude the role of hydrogen for CO_2 conversion and as feedstock for industry. To determine the range in total hydrogen use and to calculate the averages in the comparison of different types of studies (corrected for the relative size of national/regional GDP), we used the data from all studies, without correcting for lacking applications. Although this influences the average use of hydrogen, the projected range remains the same. Studies that do not explicitly mention hydrogen use for specific applications or sectors are not used to calculate the average hydrogen use for these applications or sectors in Section 5.1.3.

5 Findings on the future role of hydrogen

5.1 Future hydrogen demand

Most of the studies report multiple scenarios, of which only one or two are displayed in our analysis to limit the amount of data and to ease comparison. To acquire the broadest range possible, at least the scenario with the highest projected amount of hydrogen use is included. Figure 2 depicts how the projections in hydrogen demand vary over the different studies. At the starting point (2015) the hydrogen demand in the Netherlands ranges between 0 and 110 PJ/yr. This discrepancy is caused by the assumptions made in the studies. The low estimate is explained by the fact that some studies only analyze the (future) demand for energetic use of hydrogen, which is currently nearly zero in the Netherlands. In other studies, the current non-energetic use of hydrogen is included leading to a high value of 110 PJ/yr.

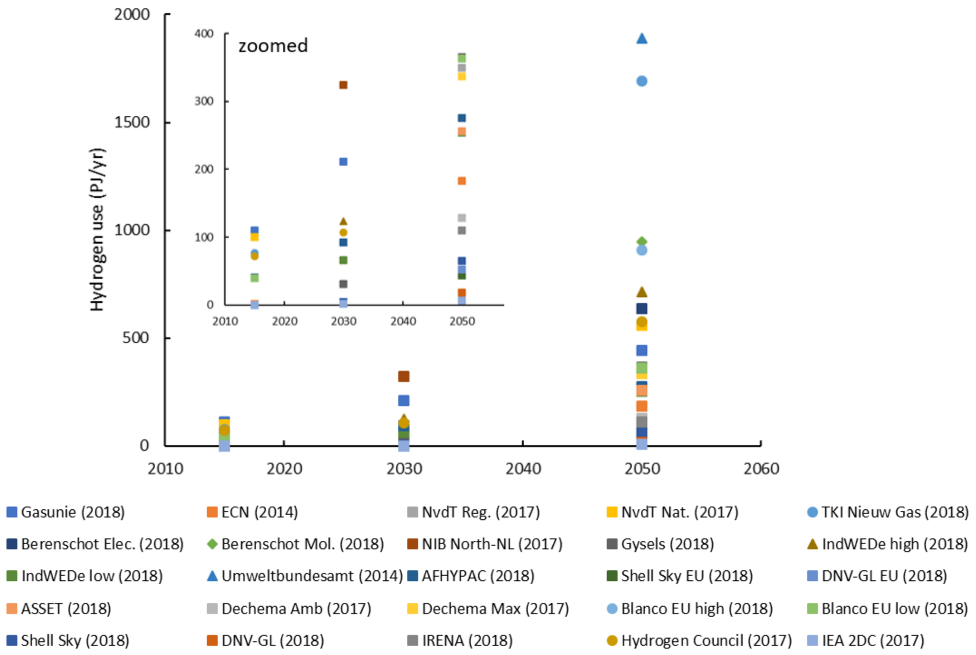

Figure 2: Total hydrogen use in the Netherlands, including some other countries and regions (values for other countries or regions are GDP corrected)

Only few data points are found for 2030, but more studies look further ahead and model or envision the situation in 2050 (or in a zero-emission society). The projected hydrogen demand in 2050 covers a broad range, namely between 0 and almost 1900 PJ/yr (or from 0 to almost 16 Mt/yr). In the most conservative studies, the role of hydrogen is negligible in comparison to total energy consumption and no substantial market for green hydrogen develops before the half of this century. In these studies (e.g. DNV GL, 2018; IEA, 2017; Shell, 2018) the potential of hydrogen is recognized but its penetration before 2050 is still considered as limited.[1] In for example the Sky scenario (Shell, 2018), which gives a projection until 2100, hydrogen use starts to

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[1] Differences between grey, blue, and green hydrogen are explained in Section 5.2.

develop from 2040 onwards and is deployed at scale only in the second half of the century.

Overall, we observe an upward trend in the projected hydrogen demand over time. The broad range of the projections reveals that there exist large uncertainties on the future role of hydrogen in the energy system. Two studies stand out in their estimate of the potential demand for hydrogen: *Outlines of a Hydrogen Roadmap for the Netherlands* (TKI Nieuw Gas, 2018)[2] and *Germany in 2050 – a greenhouse gas-neutral country* (Umweltbundesamt, 2014). In both studies a significant amount of hydrogen is required to convert CO_2 into carbon-based products, such as methane, kerosene and diesel, and feedstocks for chemical products and materials. These two studies strongly influence the averages in our analysis, but they seem very relevant if one wants to understand which factors (and underlying assumptions) lead to a high potential of future hydrogen use.

5.1.1 Regional and country effects

Figure 3 presents the use of hydrogen per sector (and in total) in 2050 as projected in the reviewed studies covering either (i) the Netherlands, (ii) other individual EU countries (notably Germany, France or Belgium), (iii) the EU as a whole, and (iv) the world as a whole (where the projected numbers for other countries or regions besides the Netherlands have been corrected for the relative size of their GDP). In addition, Figure 3 also shows the average hydrogen use over the studies covering each of these four geographical categories (indicated by the vertical dash line in Figure 3). We note that the average use throughout our analysis is probably relatively high because we have, if multiple scenarios are reported in the consulted studies, mainly selected the high hydrogen demand scenarios (as mentioned above).

Figure 3 shows that the average GDP corrected total hydrogen use in 2050 across the studies covering either the Netherlands or other individual EU countries (Germany, France or Belgium) is more or less similar (i.e. almost 700 PJ/yr), while it is substantially lower for either the EU or the world as a whole (i.e., 300 and 160 PJ/yr, respectively). Based on the available information provided in the studies considered, these differences in projected average hydrogen use cannot be explained. We think they are related to the basic characteristics and the related underlying modelling assumptions regarding the countries and regions concerned (notably on the availabilities and costs of hydrogen and other, competing energy sources).

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[2] The TKI Nieuw Gas study gives only an outline on how the use of hydrogen may evolve in the future. The final year is not mentioned, but we have positioned it at 2050 to allow comparison with most of the other studies.

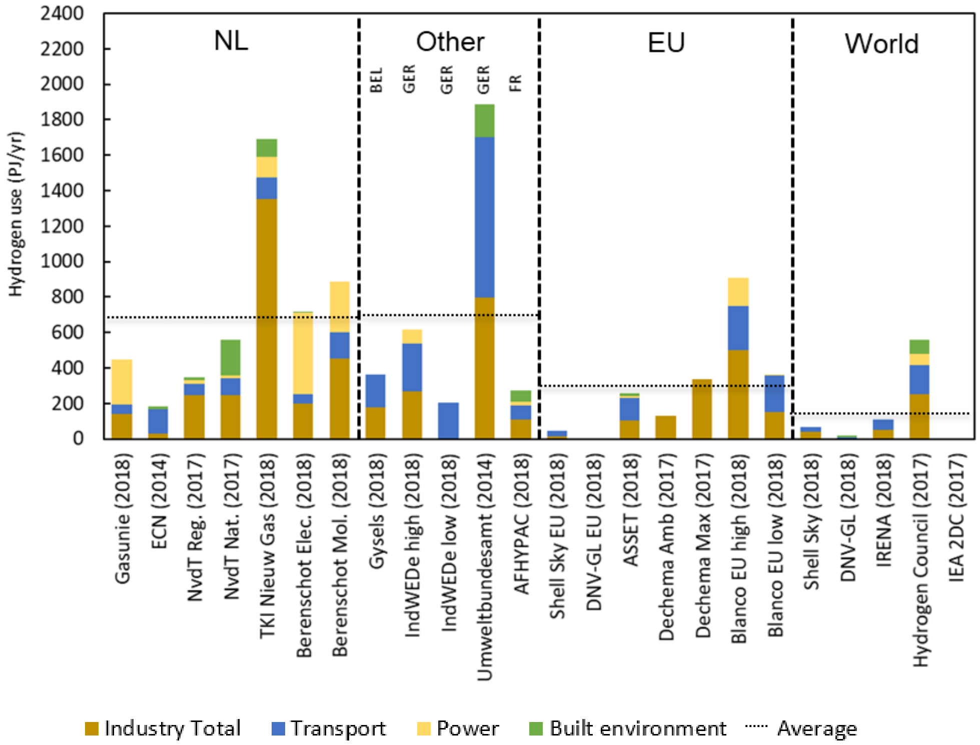


Figure 3: Hydrogen use per sector in 2050 (values for other countries or regions besides the Netherlands have been corrected for their relative GDP size)

The four colors in the bars in Figure 3 indicate the four end-use sectors in which hydrogen is used. Although some studies cover only one specific sector (e.g. industry in the Dechema study), most studies take all sectors into consideration. In several bars one or more colors are lacking, which apparently indicates that in these sectors hydrogen use is not expected to occur under the assumptions of the scenario. In Section 5.1.3 (and Chapter 6) we try to address in more detail why these differences are observed.

5.1.2 Model or vision

Categorization of the results according to the type of study, being either modelled or visualized, indicates that a clear difference in average use of hydrogen exists between models and visions, in which the latter shows a higher average use (respectively, 331 and 692 PJ/yr, Figure 4). The higher average for the visions is mainly caused by the two highest estimates (Umweltbundesamt, 2014, and TKI Nieuw Gas, 2018) that belong to this category. Interestingly, the next two highest estimates (Blanco EU high, 2018, and Berenschot Molecules, 2018) are both modelled scenarios, either using an optimization model or a simulation model, and project a higher hydrogen use than the seven other visions. This indicates that the results are mainly determined by the assumptions made by the scenarists/modelers and the input parameters used in the models. The differences in assumptions can already be seen by the distribution of hydrogen use over the sectors (indicated by the different colors). The variation per sector and the underlying assumptions are discussed in more detail in the next section (5.1.3).

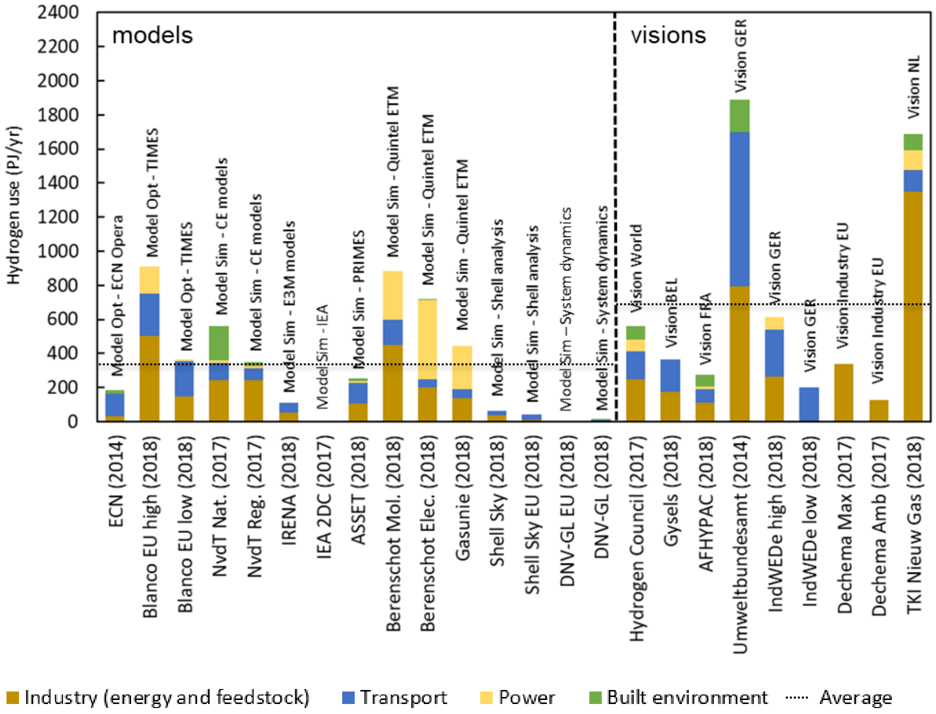


Figure 4: Hydrogen use per sector in 2050, categorized per type of study

5.1.3 *Sectors and applications*

The estimates for hydrogen use in the future vary widely among studies and sectors. In this section we describe some of the underlying assumptions that cause the existing ranges for each end-use sector. We show the results from the studies by plotting two ranges of hydrogen use in 2050: low (dark-colored area) and high (light-colored area) in comparison to the average of all studies for which a value is reported for the sector concerned (see example in Figure 5). The low range starts in each case at zero and extends until the average, while the high range starts at the average and stretches until the maximum value from all studies. Alongside of the high range bar, we note the main assumptions to reach these high projections of hydrogen use.

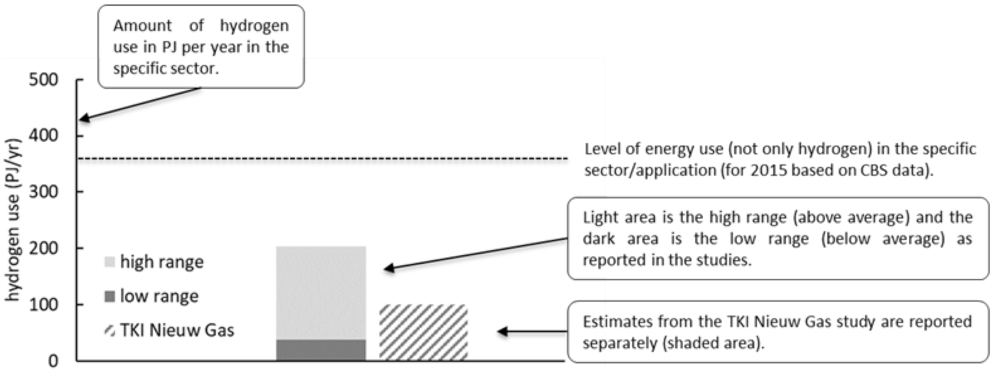


Figure 5: Example of how we illustrate the results for each sector

Next to the low and high ranges, the results from the TKI Nieuw Gas study have been depicted separately because these estimates are based on clear assumptions and help to understand to what extent these assumptions affect the level of hydrogen use for a specific application or sector. The dashed line in the figures, which indicates the 2015 level of energy use in the sector concerned, also assists in putting the amount of hydrogen use into perspective of current energy demand by a specific application or sector.

Buildings

In the built environment our main energy source for heating today is natural gas. Energy savings are expected by increased insulation and the use of more efficient energy demand appliances resulting in a lower energy use in this sector by 2050. Electric heat pumps and boilers, geothermal systems and industrial waste heat via heat networks are expected to provide the main part of heat for buildings. However, for some locations these solutions are not sufficient, practically not feasible or more expensive than using the existing gas network. For these cases, renewable gas in the form of biogas, synthetic methane, or hydrogen can replace natural gas and provide a sustainable alternative. The share of renewable gas and the portion of hydrogen in it depends on the relative costs and availability of the alternatives. In some studies, a zero demand for hydrogen is expected, while in others half of energy demand (approximately 200 PJ/yr) for heating buildings is provided by hydrogen gas (Figure 6). The average projected hydrogen use is only 34 PJ/yr, mainly because in roughly half of the studies hydrogen is not used to generate low temperature heat.

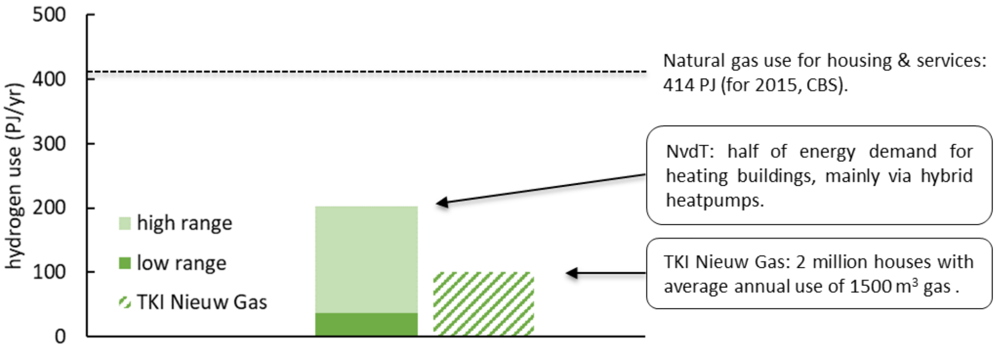
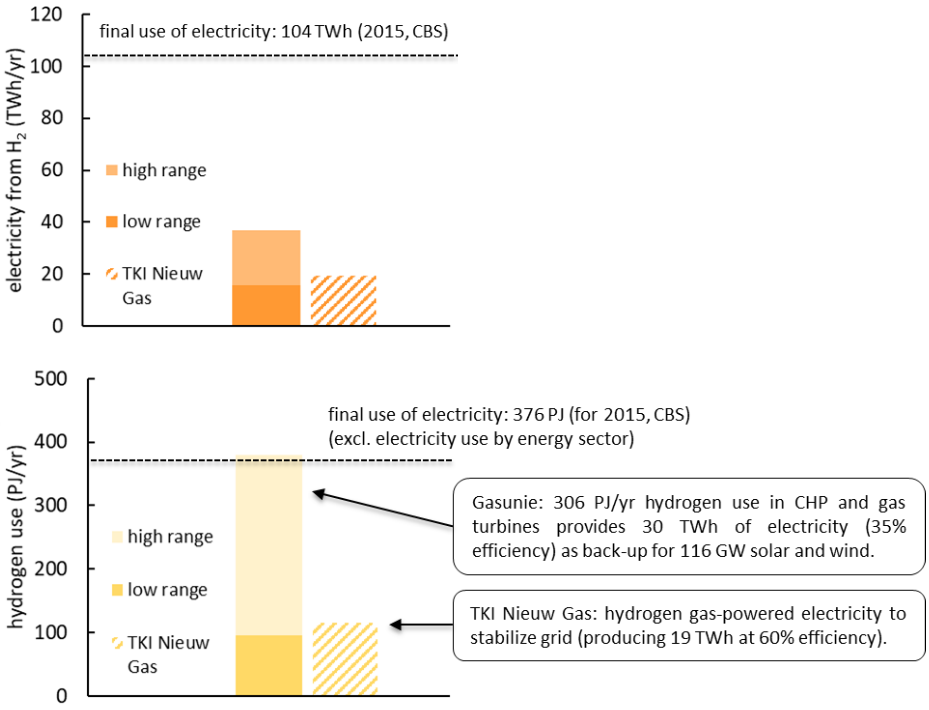


Figure 6: Hydrogen use in 2050 in the built environment

Power

The relation between hydrogen and electricity may be twofold. On the one hand hydrogen may be produced using electricity (power-to-hydrogen) while, on the other hand, electricity may in turn be generated by using hydrogen as a fuel (hydrogen-to-power). Power-to-hydrogen is one of the routes to produce hydrogen and is discussed in more detail in Section 5.2. In this section we describe the role of hydrogen as a fuel to generate electricity.

Currently electricity production in the EU mainly relies on power plants running on fossil fuels. The closure of coal and nuclear power plants and a steady increase of renewable power supply from solar and wind drastically changes the electricity system. Flexibility options that can improve the balancing and reliability of the power system include flexible (dispatchable) power generation, demand response, energy storage and (cross-border) power trade. It is expected that a specific share of power production should remain dispatchable to function as a back-up and flexibility option for intermittent renewable energy supply. These dispatchable power plants should be able to respond fast when necessary. The concept climate agreement for the Netherlands states that to ensure the security of electricity supply sufficient dispatchable power is essential, which should become increasingly free of CO_2 emissions (SER, 2018). While many studies do not expect any hydrogen use for future power supply, some studies do foresee a substantial role for dispatchable, hydrogen fueled power plants, including fuel cells and CHP plants (Figure 7). Often these solutions come up if both (intermittent) renewable electricity supply and emission reduction targets are high. In the upper graph of Figure 7, the projected hydrogen-fueled electricity production is depicted in TWh/yr to enable comparison with current electricity use. The total amount of hydrogen expressed in PJ/yr (lower graph of Figure 7) is relatively higher because of estimated efficiency losses of 35–60% in the conversion processes to produce electricity.



Gasunie: 306 PJ/yr hydrogen use in CHP and gas turbines provides 30 TWh of electricity (35% efficiency) as back-up for 116 GW solar and wind.

TKI Nieuw Gas: hydrogen gas-powered electricity to stabilize grid (producing 19 TWh at 60% efficiency).

Figure 7: Hydrogen use in 2050 for electricity production

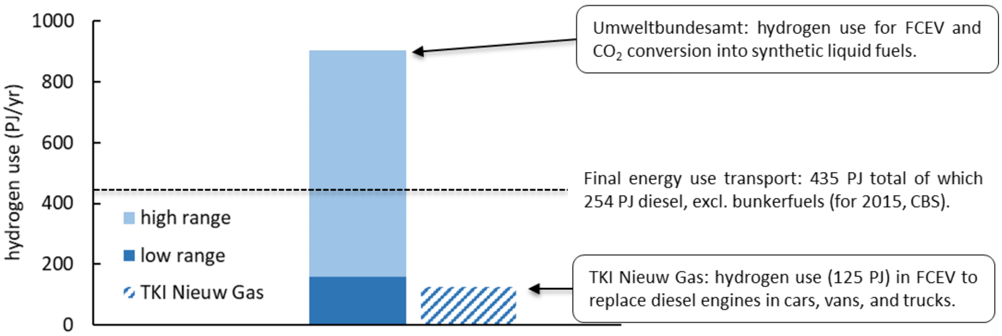
Transport

Currently, hydrocarbon fuels, derived from fossil oil, are the main energy source for transport. Energy use in the domestic transport sector in the Netherlands accounts for more than 400 PJ/yr, while bunker fuels for international aviation and shipping represent almost 700 PJ/yr. The emissions of the latter category are not part of the national CO_2 emissions bookkeeping and are thus usually not considered in national studies and scenarios.

In European and global studies, energy use for international aviation is included in the energy demand figures, while marine bunker fuels are only included in the energy demand accounts of the transport sector in global analyses. This bunker fuel demand may thus cause slight variations in the projections for hydrogen use. However, in our analysis we do not observe a clear relation between hydrogen use and an increased energy demand by aviation and shipping (in the European and global assessments).

Only considering road transport, many studies project a rapid shift to BEVs for cars and other light duty vehicles. Heavy duty vehicles, such as trucks, are more difficult to electrify. In this category the assumptions differ, and hydrogen sometimes plays a significant role as fuel in FCEVs. Alternative options for hydrogen are, besides batteries, bio-, fossil, and synthetic hydrocarbon fuels. The respective performances (e.g., in terms of costs, emissions, noise, pollution, and driving range) will determine the relative share of each of these options. The same alternatives exist for aviation and shipping but with other requirements for the fuel. As a fuel with a high energy density is preferable in these categories of transport, renewable hydrocarbon fuels seem most promising but direct use of hydrogen may be an option too.

Correcting study results for the relative GDP size of the countries or regions considered shows that almost each study projects in 2050 at least 10 PJ/yr of hydrogen use in the transport sector. The average use is 160 PJ/yr, while the highest estimate reports more than 900 PJ/yr mainly for synthetic fuel production (Figure 8). Under the assumption that all diesel engines are replaced by hydrogen-driven FCEVs, hydrogen use by road transport is around 125 PJ/yr (TKI Nieuw Gas, 2018). If diesel is replaced by synthetic hydrocarbon fuels produced from CO_2 and H_2, hydrogen demand increases further due to efficiency losses in the conversion process. Synthetic hydrocarbon fuels for aviation and shipping are more likely to become reality and have a substantial impact on hydrogen use (>700 PJ/yr) if they have to replace all current bunker fuels in the Netherlands. Some studies count the hydrogen use for these processes to the transport sector (e.g. Umweltbundesamt, 2014), while others appoint this to industry (e.g. TKI Nieuw Gas, 2018).



Umweltbundesamt: hydrogen use for FCEV and CO_2 conversion into synthetic liquid fuels.

Final energy use transport: 435 PJ total of which 254 PJ diesel, excl. bunkerfuels (for 2015, CBS).

TKI Nieuw Gas: hydrogen use (125 PJ) in FCEV to replace diesel engines in cars, vans, and trucks.

Figure 8: Hydrogen use in 2050 in the transport sector

Industry

In 2015, most primary energy sources in the Netherlands were consumed in the industrial sector with an energetic use of 554 PJ/yr and a non-energetic use of fossil fuels as feedstock of 504 PJ/yr (see Figure 9). In a recent perspective from the World Energy Council Netherlands a case is presented in which hydrogen-based technologies in industry can act as catalyst for the deployment of a hydrogen economy (WEC NL, 2019). Industrial processes often require high temperature heat, which is generally generated by the combustion of natural gas. Ninety percent of the reported studies projects a role for hydrogen to provide high temperature heat for industry in 2050. Although electricity-driven heating systems seem promising to generate low temperature heat in buildings, alternatives that can produce high temperature heat of more than 250°C are less common Replacing natural gas by hydrogen is expected to become attractive to decarbonize high temperature heat demand in industry. If current heat demand stabilizes, approximately 100 PJ/yr of hydrogen is required to replace this share of natural gas.

More hydrogen (up to 288 PJ/yr) is required if hydrogen is first converted in synthetic methane by reaction with CO_2, as described in a study for Germany (Umweltbundesambt, 2014). This route suffers, however, from additional investments in conversion equipment and efficiency losses. We should note that the Dutch situation allows for the construction of a dedicated hydrogen infrastructure fairly easily, which renders prior conversion to methane unnecessary (Gasunie and TenneT, 2019).

The relative performance of the many alternatives to provide high temperature heat, such as electric heating, solar and geothermal technology, and biomass and waste to heat options, will eventually determine the actual share of hydrogen use for heating. Currently it is still a challenge for most alternative options to provide temperatures >500°C in a practical manner. Therefore, it seems not surprising that in most studies a substantial role is projected for hydrogen use for heating purposes in industry.

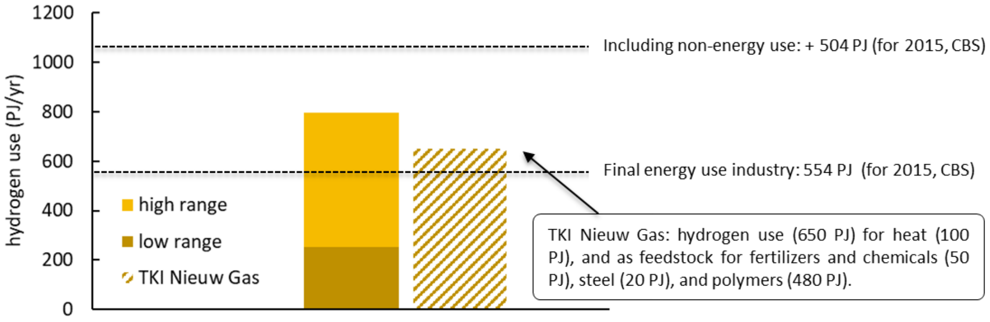


Figure 9: Hydrogen use in 2050 in industry

The projections increase substantially if hydrogen is also used as feedstock in industry. Hydrogen, produced from natural gas, is already used today at a scale of approximately 110 PJ/yr as feedstock in chemical processes, for instance to produce ammonia. Also, most common base chemicals, which are required to manufacture chemicals and polymers, have a fossil origin. Nowadays naphtha and gas condensates are the main carbon-based feedstocks for the petrochemical industry. Technology to convert CO_2 and hydrogen to synthesize base chemicals is already available, e.g. methanol synthesis and the methanol to olefins process, and Fischer-Tropsch (FT) synthesis of hydrocarbons. Implementation of such technology can reduce the consumption of fossil resources to produce carbon-based products. Production of most common base chemicals by utilization of CO_2 and H_2, increases hydrogen demand to at least 480 PJ/yr, which is the current amount of non-energy use of oil products (TKI Nieuw Gas, 2018).

Hydrogen may also be used as reductant in metallurgy, e.g., for steel production and refinery processes. The latter category might diminish if hydrocarbon fuel use decreases. This, however, may not become reality if approaches to produce synthetic hydrocarbons are deployed to provide our need for renewable carbon-based transport fuel (see also Section 5.1.3 Transport) and base chemicals. In such scenario, refining of the crude products from CO_2 conversion processes (e.g., from FT synthesis) remains necessary. Industry based on the utilization of pure CO_2 will result in the highest hydrogen demand. Next to CO_2 from industrial point sources or air, carbon feedstocks can also be derived from biomass or plastic waste. These carbon materials already contain energy and would require less additional hydrogen for their conversion. The relative availability of carbon resources thus determines the demand for hydrogen to produce renewable base chemicals, polymers, and fuels of the future.

5.2 Future hydrogen supply

Steam reforming of fossil fuels, mainly natural gas, currently provides nearly all hydrogen for industrial use. In this process the carbon is mainly emitted in the form of CO_2. In the ammonia industry a part of the CO_2 is captured for use in follow-up processes, in particular urea synthesis. Hydrogen produced from fossil fuels, accompanied by CO_2 emissions, is also referred to as ***grey hydrogen***.

For future hydrogen supply, the role of routes to produce hydrogen from fossil fuels while capturing and storing the CO_2 emissions is also explored. This so-called ***blue hydrogen*** often originates from the decarbonization of natural gas by steam methane reforming (SMR) or autothermal reforming (ATR) with carbon capture and storage (CCS). Conventional production plants are equipped with carbon capture technology, which can avoid up to about 90% of the CO_2 emissions. The captured CO_2 is compressed and exported to permanent underground sequestration sites, for instance into depleted gas or oil fields in the North Sea.

Hydrogen production without CO_2 emissions is called **green hydrogen**. Water electrolysis driven by renewable electricity is the prime example of such a process. A major benefit of green hydrogen production by electrolysis is that, during periods of excess power production from variable renewable energy, electricity can be converted into hydrogen by ramping up electrolyser capacity as a demand response option to balance the electricity system.

Other ways to produce green hydrogen exist, for instance via gasification of biomass. For this route the availability of biomass is crucial for the hydrogen production costs. In a process with biomass as feedstock, the combination with CCS can even lead to the production of hydrogen with negative emissions.

In 2050, the high CO_2 emission reduction targets for the energy system (95-100%) probably only allow supply of zero-emission hydrogen. In the reviewed studies the ratio between blue and green hydrogen supply varies from fully blue to entirely based on green hydrogen. Multiple factors, including the relative costs of blue and green hydrogen (either domestically produced or imported), the potential for CCS, the ambition of the emissions reduction target, the availability of enough renewable electricity, and the performance of the required conversion technology, determine the resulting hydrogen supply chain. On the long term green hydrogen production is the most sustainable solution, but in the short to medium term – i.e. during the initial growth phases of hydrogen as an energy vector, a transitional role for blue hydrogen seems likely (Figure 10). The projected output shares of different hydrogen production routes rely in particular on their relative competitiveness, as affected by the factors mentioned above (see also CE Delft, 2018 and FCH2JU, 2019).

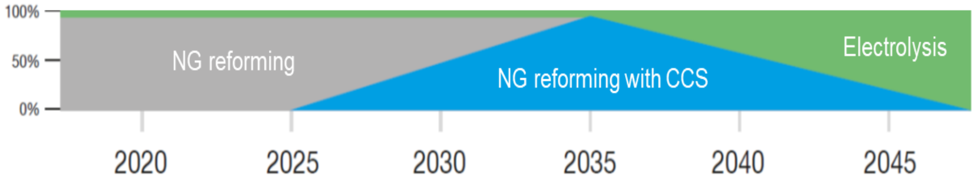


Figure 10: Illustration of a possible trajectory of the relative shares of different hydrogen production routes during a transition period. Source: TKI Nieuw Gas, 2018.

Another factor influencing the supply chain is regulation. In some countries or regions specific targets have been set by law, which commits the market to use a certain amount of (renewable) hydrogen. In California, a law from 2006 states that at least 33.3%, on a statewide basis, of H_2 produced for, or dispensed by, fueling stations that receive state funds should be made from renewable energy resources (Senate Bill, 2006). The French government has set a goal of 10% green hydrogen by 2023 and will probably increase this share to 20-40% by 2027 (Hulot, 2018).

According to the revised renewable energy directive of the European Union (RED II, 2018) "*each Member State shall set an obligation on fuel suppliers to ensure that the share of renewable energy within the final consumption of energy in the transport sector is at least 14% by 2030*" (Article 25). This share can be fulfilled by biofuels, electricity, renewable liquid and gaseous transport fuels of non-biological origin (RFNBO), and recycled carbon fuels (RCF). These latter two categories include fuels such as green hydrogen or synthetic hydrocarbons produced by the use of green hydrogen. The share of renewable electricity used to produce these fuels counts for the calculations of the 14% target. Electricity obtained from an additionally installed renewable electricity source, which is directly coupled to the fuel production process, may be fully counted as renewable electricity. It is stated that the energy content of biofuels counts twice and the energy content of renewable electricity when supplied to road vehicles even four times towards the target, but counting factors for RFNBO and RCF are not specifically described. As defined in the RED II as well, for heating and cooling renewable energy targets have to be reached to which green hydrogen can contribute.

Assuming the quality of blue and green hydrogen is sufficient, both can be used for all applications. For now, it is difficult to estimate how economical, societal, and regulatory factors influence the future hydrogen supply chain. There are, however, some applications for which the use of either blue hydrogen, as a decarbonized form of natural gas (if CCS is accepted), or green hydrogen is not straightforward from an efficiency point of view. As an example, the route to generate electricity via green hydrogen, if obtained by electrolysis, seems unlikely because the renewable electricity, which is required to produce the hydrogen, can also be used directly. This less efficient route may, however, become attractive if the system is put under severe constraints (e.g. no/low CCS and high emission reduction targets) or if different sectors can mutually benefit from e.g. shared energy storage facilities.

Future supply of hydrogen in the Netherlands can consist of domestic production, based on domestic (low-carbon) energy sources – including sources from the Dutch part of the North Sea – and/or imports from other countries, both inside and outside the EU. The ratio between domestic production and foreign imports of hydrogen depends primarily on the relative costs of these two options, including the costs of transport, etc. This ratio may depend also on political considerations, for instance the extent to which the Netherlands – or the EU as a whole – is willing to depend on foreign resources for its energy security.

5.3 Future hydrogen infrastructure

Currently, hydrogen is primarily produced and consumed by industry, while some facilities for transport and distribution of hydrogen exist across the industries involved (see also Chapter 2). Increase of future demand and supply of hydrogen will depend on a dedicated national transport and storage infrastructure with cross-border connections. If enough renewable electricity is available, green hydrogen could be produced in or close to areas where renewable energy is harvested, e.g. near offshore wind parks, in order to limit investments in relatively expensive electricity distribution infrastructure as much as possible. These production sites have to be connected via pipelines to the existing gas infrastructure. The recently published Infrastructure Outlook 2050 by Gasunie and TenneT (2019) concludes that the location, capacity and operation of power-to-gas (hydrogen) installations are decisive for (expensive) peak load investments in power networks and, hence, have to be aligned with both electricity and gas TSOs in order to integrate and optimize future infrastructure investment needs and costs.

An alternative onshore option to transport hydrogen is by means of trucks, either after liquefaction or compression, to for instance filling stations for the transport sector.

In the Netherlands an extensive, cross-border infrastructure is available for natural gas. At present, hydrogen can (due to legal and technical reasons) only to a certain limit be injected in the natural gas grid. It is possible, however, to convert natural gas pipelines into hydrogen pipelines (DNV GL 2017; KIWA, 2018). According to the recent Infrastructure Outlook 2050 (Gasunie and TenneT, 2019), the conversion of the present Dutch gas network and split into a hydrogen (transmission) network and a methane (distribution) network is fairly straightforward and has sufficient capacity. Conversion of (segments of) the existing natural gas network into a hydrogen network will serve as an enabler for the development of the hydrogen option. These existing gas grids can connect the different industrial clusters rather easily and facilitate the roll-out of hydrogen throughout the other end-use sectors.

In the existing gas network buffering for peak demand can be solved by storage of natural gas in underground gas fields and salt caverns. Storage of hydrogen in salt caverns is already a proven technology (TNO, 2018). Storage in old gas fields is less developed and traces of natural gas might decrease the purity of the hydrogen. Nevertheless, hydrogen can play an important role as a seasonal storage option for both the electricity, gas and heat sectors, thereby providing stability and supply security to the entire energy system.

The existing natural gas network can be used not only for the transport, distribution and storage of domestically produced hydrogen – including on the North Sea – but also for the import of renewable hydrogen. Import of renewable hydrogen is, however, also possible as ammonia, in which hydrogen is bonded to nitrogen, or as carbon products, such as liquefied synthetic natural gas, methanol, or hydrocarbons. For most of these energy carriers dedicated infrastructure already exists.

5.4 The wider system role of hydrogen

In addition to its various sectoral demand applications and supply options (see previous sections), the future role of hydrogen may include wider energy system functions, in particular enhancing the integration, reliability and flexibility of a sustainable energy system based largely on variable renewable energy sources, such as sun and wind, in a cost-effective way (TKI Nieuw Gas, 2018; ASSET, 2018). More specifically, as mentioned before, the production of green hydrogen by means of electrolysis offers the opportunity to integrate large amounts of renewable energy from sun and wind into the energy system, notably in hours when there is a surplus of these variable renewable energy (VRE) sources. Green hydrogen can in turn be used to generate electricity as a dispatchable back-up option during (longer) periods of VRE shortages under highly stringent carbon neutrality conditions for the power system.

Moreover, by means of both demand response and energy storage, hydrogen offers a large potential for system flexibility over different time scales, varying from supplying frequency control on power balancing markets (within a few seconds or minutes) to large-scale, seasonal energy storage for the energy system as a whole (including both electricity, gas and heat). In addition, due to its various applications across different energy sectors and its infrastructural advantages (i.e. relatively cheap and easy ways of transport and storage), hydrogen enhances the system integration and coupling of various energy sectors and markets and, hence, enhances the potential for safeguarding the reliability and flexibility of the energy system. Therefore, in addition to its various sectoral applications and supply options, these wider system functions of hydrogen should be adequately addressed when modelling and analyzing the future role of hydrogen in the energy system.

6 Summary of key findings and implications

Depending on a variety of underlying factors and uncertainties, hydrogen is expected to play a growing role in achieving a sustainable, climate-neutral energy system by 2050. In brief, hydrogen can be used for a variety of applications in almost all energy end-use sectors (i.e., hydrogen demand), which can be met by hydrogen produced domestically and/or imported (i.e., hydrogen supply), with major implications for power and gas infrastructure – including storage – depending on differences in time and place of hydrogen demand and supply. In addition, hydrogen may play a key, growing role in enhancing the integration, reliability and flexibility of a sustainable energy system based largely on VRE sources such as sun and wind.

Based on the review of recent studies presented in the previous chapter, the current chapter summarizes briefly the key findings on the major factors determining the future role of hydrogen in the energy system, notably in the Netherlands (Section 6.1). Subsequently, Section 6.2 discusses briefly the main implications in terms of (integrated) energy system modelling and analysis in order to assess the future role of hydrogen in an adequate way.

6.1 Factors determining the future role of hydrogen

Future hydrogen demand

The future demand for hydrogen is highly uncertain and depends largely on assumptions regarding the key factors affecting this demand. One factor is the carbon reduction target in a specific year as this factor determines the (implicit) carbon price for CO_2-emitting technologies and, hence, affects the competitiveness between these technologies and alternative, carbon-free technologies (including hydrogen-based technologies). More generally, the expected future demand for (carbon-free) hydrogen depends on assumptions regarding the availability and cost of (carbon-free) hydrogen versus the availability and costs of alternative (carbon-free) energy carriers and technologies.

To some extent, however, the factors affecting future hydrogen demand vary per end-use sector. In the *built environment*, hydrogen can, in principle, replace all current natural gas usage for generating low temperature heat. The projections show, on average, a minor role (34 PJ/yr) for hydrogen use because the estimated performance of alternatives to heat buildings is more attractive.

Key factors influencing hydrogen use in buildings include:

- The rate and level of energy savings (insulation) and, hence, the total level of energy demand for heating;
- The availability of (low-carbon) alternatives to meet low temperature heat demand, including electric heat pumps and boilers, geothermal heating systems, industrial waste heat via (district) networks, biogas, etc.;
- The costs of these alternatives, including the costs to deploy or modify electricity and gas infrastructure;
- Dependence on spatial, local and regional characteristics, such as urban versus rural areas.

In the *power sector*, hydrogen may play a substantial role as fuel for dispatchable *electricity production*. The projected average use of hydrogen in CHP, gas turbines, and fuel cells to produce electricity is 95 PJ/yr, while higher amounts (up to 380 PJ/yr) are projected when the capacity for renewable electricity generation increases.

Key factors influencing hydrogen use in the power sector include:
- Share of intermittent renewable electricity production in total power mix;
- Total power demand, including level of electrification in the end-use sectors;
- Ambition of the carbon reduction target for the power sector (up to 100%);
- Performance and availability of alternative fuels (e.g., biogas);
- Potential of other flexibility options, such as flexible (dispatchable) power generation, demand response, energy storage and (cross-border) power trade;
- Availability and acceptance of CCS, and relative performance of pre- and post-combustion capture technology.
- Availability of hydrogen storage.

The *transport sector* in almost all studies relies heavily on electrification to reach its CO_2 emission reduction target. Often BEVs dominate mobility, although in almost each study a specific share is satisfied by FCEV leading to an average projected hydrogen use of 160 PJ/yr. This demand is mainly ascribed to replace diesel engines for heavy transport to maintain a reasonable driving range for this category of vehicles. In a few studies synthetic hydrocarbons fulfill a substantial role as fuel for transport. If such synthetic fuels are produced domestically from CO_2, hydrogen demand increases drastically.

Key factors influencing hydrogen use for mobility include:
- Availability and performance (costs, noise, pollution, driving range, comfort, etc.) of alternative zero- or low-emission fuels (e.g. biofuels);
- Performance of BEVs and availability of charging points, including required electricity grid expansion;
- Performance of synthetic fuels (availability, costs, sustainability);
- Availability and costs of hydrogen filling stations.

In *industry*, hydrogen is an attractive fuel to replace current demand of natural gas for heating purposes, especially for very high temperature heat (>500 °C). Energetic use of hydrogen for industry ranges between nothing and almost 300 PJ/yr. Projected demand increases when hydrogen is also utilized as feedstock for ammonia and steel production and very significantly if CO_2 conversion processes to manufacture base chemicals and hydrocarbon fuels are included. Total hydrogen use in industry could increase to almost 800 PJ/yr, excluding transport fuel production, in 2050 (Umweltbundesambt, 2014). Despite a few very high estimates, the average projected hydrogen use in 2050 by industry is 254 PJ/yr.

Key factors influencing hydrogen use in industry include:
- Performance and availability of alternative, low-carbon technologies to supply heat;
- Deployment of novel industrial processes, in which H_2 is used as feedstock;
- Scale-up of CO_2 utilization industry to produce carbon-based chemicals and fuels;

- Ambition of the emissions reduction target for industry;
- Availability and performance of CCS.

Future hydrogen supply

In terms of CO_2 emissions, the supply of hydrogen is usually classified into the categories of grey, blue and green hydrogen, with each category consisting of some different process or production technologies.

Key factors affecting the type and production technology of future hydrogen supply include:

- Ambition of the carbon reduction target for the energy system as a whole;
- Potential and costs of CCS;
- Availability and cost of sufficient renewable energy;
- Availability and costs of (sustainable) biomass;
- Future development and (cost) performance of conversion technologies to produce hydrogen;
- Regulation on hydrogen production, including renewable energy supply obligations.

Apart from the different types of conversion technologies to produce hydrogen, the future supply of hydrogen can be produced domestically and/or imported from abroad. The ratio between domestic production and foreign imports of hydrogen depends primarily on the relative costs of these two options, including the costs of transport, etc. To some extent, however, this ratio may depend also on political considerations, e.g. the extent to which the Netherlands – or the EU as a whole – is willing to depend on foreign resources for its energy security.

Future hydrogen infrastructure

The future role of hydrogen in infrastructure – including storage, investment capacity needs and costs – depends, in general, on the differences in space and time between future hydrogen demand and supply.

More specifically, key factors influencing future hydrogen infrastructure include:

- Level and structure (location/time profile) of hydrogen demand and supply;
- Extent to which the current gas network can be converted or modified into a network for the transport, storage and distribution of hydrogen (including H_2 derivates such as methane);
- Location, capacity and operation of power-to-hydrogen installations (which are decisive for peak-load investment in power and gas networks);
- Ownership and regulation of hydrogen infrastructure.

Future, wider system role of hydrogen

In addition to its various sectoral demand applications and supply options, the future role of hydrogen includes probably also potential wider energy system functions, in particular enhancing the integration, reliability and flexibility of a sustainable energy system based largely on variable renewable energy sources, such as sun and wind, in a cost-effective way.

Key factors affecting this future system role of hydrogen include in particular:
- Level of electrification of the energy system, including the future deployment of ‘power-to-X’ technologies such as power-to-gas, power-to-heat, power-to-mobility (EV), power-to-liquids, power-to-chemicals, etc.;
- Share of VRE in total electricity generation, including the ratio between sun and wind supply sources;
- Availability and performance (e.g., costs) of other, competing flexibility options and conversion technologies, such as flexible (dispatchable) power generation, VRE curtailment, cross-border power trade, storage or demand response (including storage and demand response by other ‘power-to-X’ technologies).

6.2 Implications for integrated energy system modelling and analysis

Analyzing the (potential, future) role of hydrogen – in terms of both hydrogen demand applications, supply options, infrastructural needs and wider system functions – requires an integrated energy system modelling and analytical approach. More specifically, analyzing this role in an adequate way requires ideally the following modelling features (Rösler et al., 2011; Blanco, 2018; Blanco et al., 2018b):

- *Sectoral coverage.* Given the variety of hydrogen demand applications and supply options (competing with other energy sources/carriers/uses), the energy system model should (ideally) include all main energy demand and supply sectors.
- *Technological detail.* For similar reasons, the energy system model should cover, besides hydrogen, a wide variety of (competing) energy demand and supply technologies, including details on resource constraints (availability), costs, technological learning and other relevant technology characteristics, for instance regarding system flexibility, etc.
- *Infrastructural data.* The model should cover information on key energy infrastructures (electricity, gas, heat), including data on costs, capacities at different levels (transmission, distribution, storage, interconnection between countries), etc.
- *Optimal capacity and operation.* The model should be able to determine both the capacity (optimal investment) of key energy technologies and infrastructures as well as their operation (optimal dispatch) over various time intervals.
- *Geographical scope.* The model should cover different geographical levels, varying from the local to the district, regional, (inter)national or global level.
- *Spatial resolution.* At each geographical level, the model should include some adequate spatial detail, in particular to address infrastructural or other spatial issues affecting energy demand/supply such as, for instance, cross-border energy trade or the location of VRE installations.
- *Flexibility options.* In addition to system flexibility by means of hydrogen storage/demand response, the model should include all other relevant flexibility options, such as flexible (dispatchable) power generation, VRE curtailment, cross-border power trade as well as storage/demand response by other technologies.
- *Time resolution.* In order to deal adequately with flexibility issues, the model should at least be based on hourly data (profiles), notably for the power sector

and other, closely related energy demand and supply sectors (offering flexibility to the power sector).

- *Endogenous commodity prices.* For the key commodities – electricity, hydrogen – the prices should be determined endogenously by the model in a dynamic way.
- *Trading.* Trading volumes of commodities beyond the geographic boarders of the model should be provided exogenously to the model.

It will be clear that, of course, no single model is able to address all the above-mentioned features simultaneously, in particular due to data constraints or computational limitations of the modelling hard- and software. Therefore, in practice, trade-offs between these features – or other modelling solutions – have to be applied. For instance, depending on the type of research question to be addressed, choices have to be made about the model's time resolution, level of technological detail, sectoral coverage, geographical scope, etc., in order to reduce the data or computational demands of the modelling work. Other solutions include (i) assuming certain values for certain model variables (or deriving these values outside the model), and (ii) linking the outcomes of different models with different modelling features addressing different types of modelling questions. Regardless of the selected solution, however, one should be aware of the implications of this solution, notably concerning the robustness versus uncertainty of the modelling findings.

Relevant modelling parameters

Differences in scenario modelling outcomes regarding the future role of hydrogen are usually due to differences in underlying modelling assumptions on key input parameters. Several studies have analyzed the relevance of these modelling parameters with regard to the performance of hydrogen in future, low-carbon energy systems (see, for instance, De Joode et al., 2014; Blanco et al., 2018a and 2018b; Hanley et al., 2019; as well as more specific references in these studies). Here we list the five main parameters considered in these studies:

(i) CO_2 reduction target

The principal parameter affecting the future role of hydrogen is the CO_2 reduction target of the energy system, which is usually expressed as a percentage in a certain year, for instance 90% in 2050, compared to the level of CO_2 emissions in 1990. In general, it is expected that hydrogen will only play a significant role in an energy system with a deep decarbonization target and that this role becomes larger as the target becomes stricter since there is less room for emissions coming from fossil fuels (De Joode et al., 2014; Blanco et al., 2018a and 2018b). For instance, De Joode et al. (2014) show that in most of the scenarios considered power-to-gas (including both hydrogen and synthetic methane) plays hardly or no role in energy system scenarios with a CO_2 reduction target of either 50% or 70% in 2050 but is only considered a significant part of a cost-optimal mix of technologies in the case of an 85% reduction target.[3]

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[3] The CO_2 reduction target is usually closely linked to two other variables, i.e. the CO_2 price and the share of renewables in total energy use, in the sense that if the CO_2 reduction target is higher the CO_2 price and the share of renewables are generally also higher. The CO_2 reduction target, however, is selected as the principal parameter to consider the future role of hydrogen because it is usually the main policy target to address climate change, while the other two variables are usually derived outcomes or sub-targets of this overarching target (Blanco et al., 2018b).

(ii) Carbon capture and storage (CCS)

The role of hydrogen in the energy system depends highly on the availability of CCS (including the social acceptance of this technology). In case of no or rather restricted CCS potential, other carbon mitigation options become more attractive. More specifically, such a case increases the demand for hydrogen, including the demand for H_2 derived products such as power-to-methane or power-to-liquids. Moreover, on the supply side, it enhances the need for hydrogen electrolysers to replace steam reforming of fossil gas combined with CCS (De Joode et al., 2014; Blanco et al., 2018a and 2018b; Kanellopoulos and Blanco, 2019).[4]

(iii) Biomass potential

The availability of biomass has a significant, albeit mixed impact on the role of hydrogen in the energy system. On the one hand, it acts mainly as a competitor of hydrogen, i.e. a higher availability of biomass leads to a lower demand for hydrogen, notably in industry and transport. On the supply side, however, it is also an enabler of hydrogen, i.e. a higher availability of biomass facilitates hydrogen production from biomass gasification (with or without CCS), thereby competing with other hydrogen supply options (De Joode et al., 2014; Blanco et al., 2018a and 2018b; Hanley et al., 2018).

(iv) VRE power supply

A major factor affecting the future role of hydrogen in the energy system is the supply of electricity from VRE, notably sun and wind, including the resulting need for flexibility by the power system. On the one hand, a large supply of VRE power generation may result in low electricity prices, in particular during a large number of hours throughout the year, leading to a competitive advantage of electricity-based demand technologies compared to hydrogen-based demand technologies – notably for mobility and heating purposes – and, hence, to a lower demand for hydrogen. On the other hand, i.e. on the supply side, such a situation improves also the competitive position of electricity-based hydrogen production (i.e., by means of electrolysers) compared to alternative hydrogen production technology options, leading to a change in the hydrogen supply mix. In addition, a higher variable power supply leads to a higher need for flexibility by the power system. To some extent, this higher need for flexibility may be provided by means of hydrogen – i.e. through electrolyser demand response, hydrogen storage and/or hydrogen-based dispatchable power generation – depending on the relative performance of alternative flexibility options (De Joode et al., 2014; Sijm et al., 2017; Kanellopoulos and Blanco, 2019).

More specifically, however, the study by De Joode et al. (2014) shows that (i) very high amounts of VRE power supply at 50% and 70% CO_2 reduction levels do not lead to the penetration of power-to-gas (this happens only in the 85% reduction scenario), and (ii) the availability of unlimited, alternative power system flexibility options at simulated zero cost does not reduce the system flexibility role of power-to-gas to zero

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[4] In a recent study, Kanellopoulos and Blanco (2019) show that in scenarios where CCS is considered possible, the main hydrogen production technology used (>95%) is steam reforming with CCS, thereby limiting the requirement for electrolysers across the EU (~80 GW). On the other hand, in scenarios where CCS is not widely adopted or accepted, electrolysis is the predominant technology while the system requires more hydrogen, resulting in significant electrolyser capacities (~1000 GW).

(in the 85% reduction scenario). These findings demonstrate that the need for power system flexibility is not the key driver for the role of power-to-gas (but rather that deep decarbonization is the key driver). However, once power-to-gas plays a significant role in the energy system (at deep decarbonization levels), it does contribute to the need for flexibility to some degree, while it is only partly affected by the (unlimited and free) availability of other flexibility options.[5]

***(v)* Technology costs**
The future role of hydrogen in the energy system depends also on the hydrogen technology costs compared to the costs of competing energy demand and supply technologies (both conventional and innovative, emerging technologies), including the potential for cost reductions by technological learning and efficiency improvements across the full range of these technologies (Rösler et al., 2011; De Joode et al., 2014; Blanco et al., 2018a and 2018b). These costs refer to both capital investment costs (CAPEX) and operational costs (OPEX), including fuel costs. De Joode et al. (2014) shows that a 50% reduction in electrolyser costs (compared to the reference scenario) creates a situation, possibly explained by an overall improved business case, in which the operating hours of the electrolyser and, thus, the hydrogen output can be increased by 15%. In addition, a higher level of fossil fuel prices has a positive impact on both the uptake of wind-based electricity generation and electrolysis-based hydrogen production (De Joode et al., 2014).

6.3 Closing remarks

We have shown that hydrogen is seen as a versatile energy carrier and can either directly or indirectly (i.e. by means of H_2 derivates) be used in a wide variety of final energy applications. The range of (total) projected hydrogen demand can be determined either per sector or for the energy system as a whole (at a local, national, regional or global level). On the other hand, hydrogen can be produced in a variety of ways and either supplied domestically or traded abroad. Depending on differences in time and location of hydrogen demand and supply, there is a need for hydrogen infrastructure, including transport, distribution and storage. In addition, hydrogen may fulfill a variety of wider energy system functions, notably enhancing the integration, reliability and flexibility of a sustainable energy system based largely on sun and wind.

Analyzing the (potential, future) role of hydrogen requires an integrated energy system modelling and analytical approach. We have identified five key modelling parameters: CO_2 reduction target, availability of CCS, availability of biomass, VRE power supply, and technology costs. These parameters have to be considered adequately when modelling and analyzing the future role of hydrogen in the energy system. Moreover, given the relevance – but also the uncertainty of these parameters, notably in the long run (2030-2050) – the modelling and assessment of this role should preferably also include an appropriate selection of sensitivity analyses of the potential impact of these parameters on the role of hydrogen in an integrated, sustainable energy system. In case this ideal situation is or cannot be met,

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[5] It should be noted that in addition to the power system, hydrogen may play a (more significant) flexibility role in other energy systems (gas/heat), notably by addressing variations in daily and seasonal demand patterns (although this role is also affected by alternative, competing options such as storage of green gas or heat, including geothermal energy).

for instance due to a lack of budget or data resources, one should be well aware of the implications for the robustness and uncertainty of the modelling or vision scenario findings.

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Blanco EU (2018)	Blanco, H. et al., Potential for hydrogen and Power-to-Liquid in a low-carbon EU energy system using cost optimization. Applied Energy 2018, 232, 617-639. Scenario 95 (low) and Hydrogen (high) are part of our meta-analysis.
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DNV-GL (2018)	Energy Transition Outlook, A global and regional forecast to 2050, September 2018 Energy Transition Outlook, Oil and Gas, forecast to 2050, September 2018. From these two reports, projections for both the World and Europe (EU) are extracted and used in our meta-analysis.
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B Definitions of hydrogen use

Energetic use of hydrogen

Hydrogen is applied to generate heat or power.

Examples:

- fuel for power plants;
- fuel for fuel cell electric vehicles;
- fuel for high or low temperature heat (e.g. in the natural gas network).

Non-energetic use of hydrogen

Hydrogen is applied as feedstock for a chemical process. As a result of this chemical conversion process, hydrogen, or part of its energy content, is stored in the product.

Examples:

- for ammonia production (reaction of H_2 with N_2);
- for iron/steel production (reaction of H_2 with iron oxide);
- for carbon-based chemicals production (reaction of H_2 with CO_2, e.g. to produce ethylene, formic acid, or methanol);
- for carbon-based fuels production (reaction of H_2 with CO_2, e.g. to produce methane, diesel or kerosene).

Remark: intermediate storage of hydrogen

To ease transportation of hydrogen, it may be attractive to convert it temporarily into other materials. The market demand for these materials is currently very low and their function is thus only as intermediate storage option for hydrogen.

Examples:

- liquid organic hydrogen carriers;
- metal hydrides.